Fundamental Studies In Tropical Cyclone Structure & Intensity Change

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LONG-TERM GOALS AND OBJECTIVES

Focusing on dynamical and thermodynamical processes germane to the hurricane's core region, this research aims to obtain a more complete understanding of key atmospheric processes governing hurricane structure and intensity. This year (beginning May 2002) we have continued our work on the moist dynamics of the hurricane eye/eyewall and the dry dynamics of a hurricane-like vortex in vertical shear. New insight and discoveries have been advanced in both areas. These are summarized below.

- **Hurricane Superintensity: "Turbocharging" the Carnot Hurricane Model**

APPROACH

Maximum potential intensity (MPI) theory provides a valuable tool to hurricane intensity forecasting (e.g., DeMaria and Kaplan 1999). The most widely accepted MPI theory is that of Emanuel (1986; 1995; 2000), which has been described as being consistent with a Carnot heat engine. We seek to test Emanuel's MPI (E-MPI) with a computer simulation that closely mimics many of the important assumptions of E-MPI theory (axisymmetric geometry and a constant SST that interacts with the atmosphere through simple bulk aerodynamic parameterization for moist enthalpy and angular momentum). The numerical model employed is the Rotunno and Emanuel (1987; RE87) cloud-resolving, axisymmetric hurricane model, kindly provided to us by R. Rotunno of NCAR-Boulder. This research has been conducted by J. Persing and M. Montgomery at CSU.

WORK COMPLETED

We have completed our comparison of numerical model simulations with theory, established a mechanism by which simulations may *greatly* exceed the predictions of E-MPI, and have presented this result in conference and in a research manuscript, recently accepted with revision for publication in the Journal of the Atmospheric Sciences (Persing and Montgomery, 2002). This work was sufficient to permit graduation of J. Persing with a Ph. D. degree in Atmospheric Science at CSU.

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RESULTS

With large increases in radial, vertical, and temporal resolution, the RE87 model greatly exceeds the intensity anticipated by E-MPI theory. This result is in variance with the RE87 paper, which used a very coarse resolution (radial grid spacing of 15 km). A new phenomenology is associated with the "superintensity", namely a marked enhancement in moist entropy (latent heat) in the low-level eye. A tangential vortex sheet develops on the inner edge of the eyewall, which breaks down into tangential eddies. These eddies, not accounted for in E-MPI theory, contribute by advecting the high latent heat from the low-level eye to the eyewall. As soon as condensation of this enriched air occurs, this interaction between the eye and the eyewall represents an additional source of heat for the eyewall. Figure 1 shows trajectories "seeded" in the eyewall updraft and computed both forward and backward. The red trajectories have a significant interaction with the latent heat source in the eye. These fluid particles subsequently interact with the eyewall updraft, leading to an enrichment of equivalent potential temperature (θ_e) as trajectories ascend in the eyewall. The only source of heat accounted for in E-MPI theory is that from the ocean directly below the eyewall, and thus the trajectories would rise in the eyewall with a constant θ_e. This is not the case in our simulation. With the added eye heat source, which can be crudely modeled as an enhancement of the SST, the Carnot model for the hurricane is still roughly confirmed. A complete Carnot theory for hurricane intensity needs to account for this second source of heat, in effect "turbocharging" the hurricane Carnot cycle. At this time we have not yet "closed" the problem in that we cannot anticipate *a priori* the ultimate intensity of the hurricane. The closure problem will depend on the magnitude of the low-level moist entropy enhancement (relative to the eyewall), the effectiveness of the entraining agent (tangential vortices, subgrid-scale diffusion, low-level outflow jet, etc.), and the factors already identified in E-MPI theory (surface and outflow temperature, surface relative humidity, etc.). This remains an important topic for basic research.
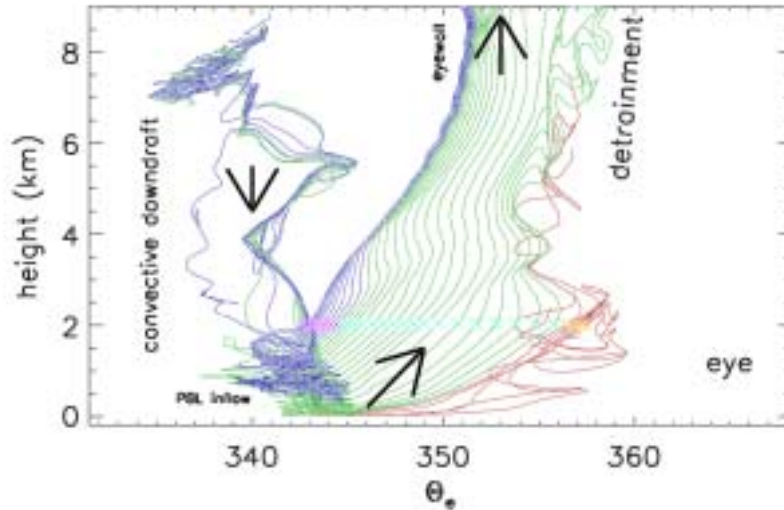

Figure 1: Forward and backward trajectories from the RE87 model "seeded" at a height of 2 km bisecting the eyewall updraft at equal spatial intervals, displayed as a function of θ_e and height. Red trajectories enter the eyewall updraft from the eye. Green and blue trajectories enter the eyewall updraft directly from the boundary layer inflow. [Eyewall updraft trajectories are seen to increase in both height (from 0 to 8 km height and beyond) and θ_e (from approx. 343 to 352 K) through otherwise smooth ascent. Left-to-right traces in the low-level eye are indicative of locally-nonconservative transfers of θ_e with neighboring parcels of air. A convective downdraft shown appears to be of no effect on parcels of air upon entry into the eyewall updraft.]

IMPACT/APPLICATIONS

There are obvious differences between axisymmetric geometry and more realistic three-dimensional geometry, among them vertical wind shear in the environment, vortex tilt, kinematic asymmetries, and convective asymmetries. We hypothesize that these act to decrease the intensity of mature hurricanes, in addition to other factors explicitly ignored in E-MPI theory, primarily wind-induced ocean mixing. In the face of these negative factors on hurricane intensity, we have identified a process (superintensity) for increasing hurricane intensity, even if hurricane intensity is well below its E-MPI. The process for creating moist air with high entropy in the eye is not special to axisymmetric geometry: low central surface pressures over a more-or-less constant sea surface temperature provides for a source of high entropy. The process for entraining this moist air into the eyewall in the axisymmetric model, tangential eddies, is certainly permitted in reality, but hurricanes typically exhibit inner-core asymmetries associated with eyewall mesovortices and vortex Rossby waves (e.g., Schubert et al. 1998; Braun 2002). We believe we have discovered and clarified an important mechanism that will alter both the MPI and the intensification rate of hurricanes observed in nature.

FUTURE WORK

We plan to investigate the superintensity phenomenon in three-dimensional hurricane simulations. We also plan to return to the axisymmetric framework to re-assess the impact of dissipational heating (following Bister and Emanuel, 1998), and the sensitivity of modeled storm intensity ("model MPI") to convective available potential energy (CAPE). We will perform a complete moist entropy budget of the eye and eyewall of the simulated hurricanes. We aim to incorporate the impacts of three-dimensional effects (barotropic instability, vertical shear, outer-core vortex Rossby waves) into a more-complete MPI theory, which could be used as forecast guidance in an operational setting.

- **Understanding the Dynamics of Tropical Cyclones in Vertical Shear**

APPROACH

Recently we proposed a new theory for the self-alignment of quasi-geostrophic (QG) vortices, demonstrating the fundamental role of vortex Rossby waves in the relaxation of tilted vortices to an aligned state (Reasor and Montgomery 2001; Schecter, Montgomery, and Reasor 2002). Although convection has been shown to contribute to the vertical alignment of tropical cyclones (TCs) (e.g., Flatau et al. 1994), we have shown that our adiabatic self-alignment mechanism operates on time scales short enough to be dynamically relevant to the TC-in-shear problem. To explore the full range of observed TC strengths and environments we have extended our QG alignment theory to finite Rossby number with vertical shear forcing using a primitive equation (PE) model linearized about a circular vortex in gradient balance. Our goal is to understand the mechanisms that determine the critical threshold between alignment and irreversible deformation of a TC in shear, building off of the pioneering sensitivity studies of Jones (1995). Comparison of our linear PE results with those from fully nonlinear dry simulations using the CSU-RAMS model (Pielke et al. 1992) indicate that vortex Rossby waves continue to play an essential role in the vertical alignment of strong TCs. This work lays the foundation for a theoretical investigation of the critical threshold for TC alignment in shear. This research is being conducted by P. Reasor and M. Montgomery at CSU.

WORK COMPLETED AND RESULTS

In the linear QG system the ratio of vortex scale to Rossby deformation radius defines the alignment phase space for a vortex of given radial structure and initial barotropic vertical structure. More generally, an additional degree of freedom must be added, the Rossby number. Using our linearized PE model, we have constructed a phase portrait for the alignment of a tilted barotropic vortex of Gaussian radial structure. The results shown in Figure 2 indicate that rapid alignment is best achieved by increasing the Rossby number from the infinitesimal values of the QG regime. The mechanism by which a tilted vortex aligns at finite Rossby number depends on where the vortex is located in this phase space. At small values of the ratio of vortex scale to deformation radius and small Rossby number the vortex supports a damped quasi mode, first identified as relevant to the vortex alignment problem by Reasor and Montgomery (2001) in the QG context. In the related problem with an imposed shear flow, if the quasi mode decay rate is too weak and the precession frequency too slow compared to the rate of differential advection, the vortex will shear apart. We have confirmed this behavior using the CSU-RAMS model (not shown). Returning to the free alignment problem (Fig. 2), at large values of both parameters the vortex no longer supports a quasi mode, but instead aligns through the redistribution of potential vorticity by sheared vortex Rossby waves. In shear flow, the vortex would remain vertically coherent through a competition between the production of tilt asymmetry by differential advection and the dispersion of that asymmetry as sheared vortex Rossby waves.
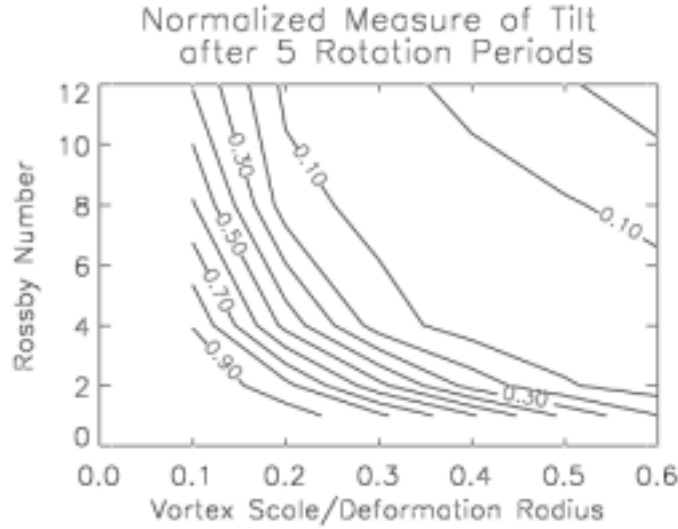

Figure 2: Azimuthal wavenumber 1 geopotential amplitude (normalized by the initial value) at the radius of maximum mean potential vorticity gradient after 5 vortex circulation periods. Small contour values indicate near-complete alignment. [The most rapid vortex alignment occurs for large Rossby number, large vortex scale, and small deformation radius.]

IMPACT AND APPLICATIONS

For the standard Gaussian vortex profiles used here, the linear theory gives an indication of where in the parameter space the vortex is most likely to resist differential advection by the shear flow and how the vortex resists such a forcing. To actually determine the critical threshold for alignment, we must include nonlinear advection. Representing a tilted vortex by point vortex columns in a two-layer model, Smith et al. (2000) showed that the precession frequency is proportional to the vortex

circulation and a coupling constant between the two layers, and inversely proportional to the square of the horizontal separation distance between upper and lower level PV anomalies. If we could determine how to relate the coupling constant to the physical parameters of our linear model, the Smith et al. approach may be useful for defining the critical threshold. It is unclear, however, whether the inability of the Smith et al. model to capture free alignment is a truly limiting aspect of their model. It is possible that the details of tilt damping become irrelevant once shear is imposed, and that the quasi mode precession is the key to understanding the critical threshold (although this could not be the case in the rapid alignment regime where the quasi mode does not exist). This is one of the primary thrusts of our ongoing research.

FUTURE WORK

Diabatic processes are an essential part of TC development, and their role has generally been regarded as favorable in keeping the vortex vertically coherent. While we do not dispute the positive role of convective momentum transports in thwarting attempts by vertical shear to tilt the vortex, to say that diabatic processes are the only reason for the robustness of TCs in shear is misleading, and likely incorrect. We have shown that the linear alignment mechanisms described above are alone capable of fighting differential advection by vertical shear.

Our future work will consider the impact of diabatic processes on the critical threshold for vortex alignment. As a first step, we will decrease the static stability uniformly in the linear PE model, which according to Figure 2 will increase the rate of self-alignment. The next step will be to impose a heat source in the vortex core, crudely parameterizing latent heat release by eyewall convection. The final step is to revisit the full-physics vortex-in-shear paradigms of Frank and Ritchie (2001) with our alignment theory. We will use a full physics model formulation with explicit convection.

TRANSITIONS

During FY2002, we plan to continue our study of vertically sheared hurricanes focusing particularly on identifying the key parameters that determine the critical threshold for shearing a hurricane vortex apart. We will examine both dry and moist problems, representing moist processes in a manner as described in this report. We will also begin a study of the formation mechanism of secondary eyewalls using full physics MM5 and RAMS simulations of these events currently being conducted for the related maximum intensity objectives described in this report.

RELATED PROJECTS

None.

SUMMARY

This year's work has focused primarily on:

a)   identifying the mechanism for hurricane superintensity in both axisymmetric and three-dimensional hurricane models;

b)   establishing a theoretical foundation for investigating the critical threshold for TCs in shear.

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PUBLICATIONS

Refereed publications during FY-2002:

Persing, J., 2002: Insights on Hurricane Intensity. Ph. D. Dissertation, Colorado State University, 132 pp.

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Reasor, P. D., and M. T. Montgomery, 2002: A vortex Rossby wave mechanism for the vertical alignment of tropical cyclones in shear. *J. Atmos. Sci.*, in prep.

Presentations during FY-2002:

Montgomery, M.T., 2002: Tropical Cyclones – Theoretical aspects: Understanding extreme intensity. June 11, IPCC Workshop on Changes in Extreme Weather and Climate Events, Beijing, China.

Persing, J.P., and M.T. Montgomery, 2002: Hurricane intensity as modeled in axisymmetric models compared to MPI theory. April 26, 25th Conference on Hurricanes and Tropical Meteorology, San Diego, CA.

Reasor, P. D., and M. T. Montgomery, 2002: Understanding the dynamics of vertically sheared hurricanes. April 26, 25th Conference on Hurricanes and Tropical Meteorology, San Diego, CA.